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Probing nucleon strangeness structure with ϕ electroproduction

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We study the possibility to constrain the hidden strangeness content of the nucleon by means of the polarization observables in ϕ meson electroproduction. We consider the OZI evading direct knockout mechanism that arises from the non-vanishing $s\bar{s}$ sea quark admixture of the nucleon as well as the background of the dominant diffractive and the one-boson-exchange processes. Large sensitivity on the nucleon strangeness are found in several beam-target and beam-recoil double polarization observables. The small \sqrt{s} and W region, which is accessible at some of the current high-energy electron facilities, is found to be the optimal energy region for extracting out the OZI evasion process.

Key words: ϕ electroproduction; Polarization observables; Vector-meson dominance model; One-boson exchange model; Quark model
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Production of ϕ mesons from nucleon targets has been suggested as a sensitive probe to study the hidden strangeness of the nucleon. This is because the ϕ is a nearly pure $s\bar{s}$ state so that its direct coupling to the nucleon is suppressed by the OZI rule. However, if there exists a non-vanishing $s\bar{s}$ sea quark component in the nucleon, the strange sea quark can contribute to the ϕ production via the OZI evasion processes. Investigation of such processes can then be expected to shed light on the nucleon strangeness content, if any. For example, recent studies on the ϕ production in $p\bar{p}$ annihilation at rest indicate a large violation of the OZI rule [1], which can be explained with the presence of an intrinsic $s\bar{s}$ component in the nucleon since it provides with additional rearrangement and shakeout diagrams [2,3].⁵

The ϕ meson can also be produced from the nucleon with photons and electrons. The dominant process in the electromagnetic production of the ϕ comes from the diffractive production (vector-meson dominance) through the Pomeron exchange, while the one-boson-exchange mechanism gives corrections mostly at backward scattering angles. In addition, the possible hidden $s\bar{s}$ cluster in the proton can contribute through direct knockout process. The knockout process was first estimated with a nonrelativistic harmonic oscillator quark model [5]. In Ref. [6], we employed a relativistic harmonic oscillator quark model (RHOQM) to include the relativistic Lorentz-contraction correction. Following the analysis of Ref. [5], we found that the theoretical upper bound of the admixture of strange sea quarks in the proton allowed for by the existing electroproduction cross section data is less than 5%. Nevertheless, it is *not easy* to discern each process in the cross section measurements because their respective contributions have similar dependence on momentum transfer. We have recently demonstrated [7,8] that many double polarization observables in ϕ photoproduction could be more useful tools in investigating the strange sea quark structure in the nucleon. In this paper, we extend our previous study to the case of ϕ electroproduction with longitudinally polarized electron beams.

In ϕ electroproduction process, $e + p \rightarrow e + p + \phi$, using one-photon exchange approximation, we define the four momenta of the initial electron, final electron, virtual photon, initial proton, final proton and produced vector-meson as k_e, k'_e, q, p, p' and q_ϕ , respectively. In the laboratory frame, we write $k_e = (E_e, \mathbf{k}_e)$, $k'_e = (E'_e, \mathbf{k}'_e)$, $p = (E_p^L, \mathbf{p}^L) = (M_N, \mathbf{0})$, $p' = (E_{p'}^L, \mathbf{p}'^L)$, $q_\phi = (\omega_\phi^L, \mathbf{q}_\phi^L)$ and $q = (\nu^L, \mathbf{q}^L)$, where M_N is the nucleon mass. In the hadronic (or γ^*p) c.m. frame, we write $q = (\nu, \mathbf{q})$, $q_\phi = (\omega_\phi, \mathbf{q}_\phi)$, $p = (E_p, -\mathbf{k})$ and $p' = (E_{p'}, -\mathbf{q}_\phi)$, respectively. We further define $s = (k + p)^2$, $Q^2 = -q^2$, $W^2 = (p + q)^2$ and $t = (p - p')^2$.

Our model for ϕ electroproduction includes the diffractive production, one-boson-exchange (π and η exchange) and the direct knockout processes as shown in Fig. 1. The OZI evaded knockout process is allowed only if the proton contains non-vanishing $s\bar{s}$ sea quark admixture. In the vector-meson-dominance model (VDM) of the diffractive production process [9,10], the incoming photon first converts into $q\bar{q}$ pair (ϕ -meson in our case) and this ϕ scatters diffractively from the nucleon target through Pomeron exchange as shown in Fig. 1(a). It has been claimed that most of the vector-meson electromagnetic production process data could be understood qualitatively

⁵ It has been, however, also claimed that this OZI violation could be understood within modified meson exchange models [4] by excluding intrinsic strange sea quark component in the nucleon wavefunction.

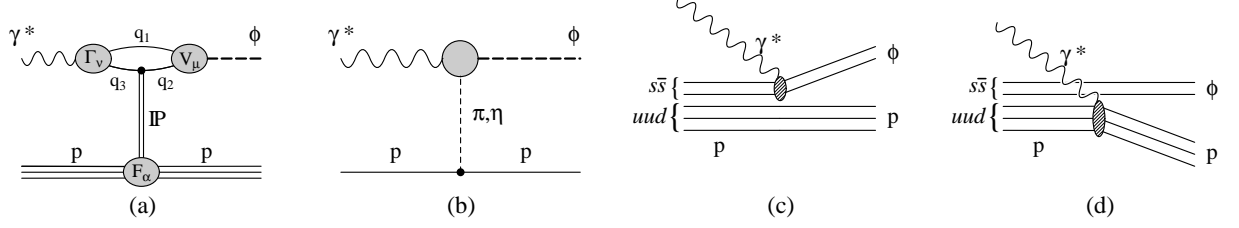


Fig. 1. Processes for ϕ meson electroproduction. (a) diffractive, (b) one-boson-exchange, (c) $s\bar{s}$ -knockout and (d) uud -knockout process.

and quantitatively by the diffractive process with the Pomeron-photon analogy [11–13].⁶ As in our previous works on ϕ photoproduction [7,8], we use the parameterization of the vector-meson-dominance model [17] together with the spin structure coming from the Pomeron-photon analogy. (See Ref. [8] for more details.)

Then the invariant amplitude of this process can be written as

$$T^{\text{VDM}} = iT_0 \varepsilon_\mu^*(\phi) \mathcal{M}^{\mu\nu} \varepsilon_\nu(\gamma), \quad (1)$$

with $\varepsilon_\mu(\phi)$ and $\varepsilon_\mu(\gamma)$ the ϕ and photon polarization vector, respectively, and

$$\mathcal{M}^{\mu\nu} = \bar{u}(p') \gamma_\alpha u(p) \left\{ (q + q_\phi)^\alpha g^{\mu\nu} - 2q^\mu g^{\alpha\nu} - \frac{2q^2}{q \cdot q_\phi} q_\phi^\nu g^{\alpha\mu} \right\}, \quad (2)$$

where $u(p)$ is the Dirac spinor of the nucleon with momentum p and we keep the relevant terms only [8].

The dynamics of the Pomeron-hadron interactions is represented by T_0 . It is parameterized according to the prescription of Ref. [18], which gives the differential cross section for virtual photoproduction as

$$\frac{d\sigma_{\gamma^*}}{dt} = \frac{\sigma_\phi(0, W)}{(1 + Q^2/M_\phi^2)^2} \frac{q^*(0)}{q^*(Q^2)} (1 + \varepsilon R_\phi) b_\phi \exp\{b_\phi[t - t_{\max}(0)]\}, \quad (3)$$

where ε is the virtual photon polarization parameter, M_ϕ the ϕ -meson mass and

$$q^*(Q^2) = \frac{1}{2W} \sqrt{[(W - M_N)^2 + Q^2][(W + M_N)^2 + Q^2]}. \quad (4)$$

The VDM hypothesis leads to that R_ϕ , the ratio of the cross sections with longitudinal and transverse photons, is $R_\phi = \xi^2 Q^2 / M_\phi^2$, where the phenomenological factor ξ^2 is to be determined

⁶ Here we do not consider the two-gluon exchange model for the Pomeron exchange [14–16].

by experiments. The parameters are fixed as $\xi^2 = 0.328$ [9,19], $\sigma_\phi(0, W) = 0.20 \mu\text{b}$ and $b_\phi = 4.01 \text{ GeV}^2$ for $W \sim 2 \text{ GeV}$ [17], and $\sigma_\phi(0, W) = 0.22 \mu\text{b}$ and $b_\phi = 3.46 \text{ GeV}^2$ for $W \leq 3 \text{ GeV}$ [9,19]. As in photoproduction [8], this amplitude is purely imaginary and has the helicity conserving form at the forward scattering angles, i.e., at small $|t|$ limit.

The one-boson-exchange (OBE) process shown in Fig. 1(b) is allowed because of the possible decays of $\phi \rightarrow \gamma\pi$ and $\phi \rightarrow \gamma\eta$. This process represents the contributions from the possible non-strange quark component in the ϕ -meson and gives a correction to the diffractive production [20]. In fact, OBE is comparable to or even dominates the diffractive process in large $|t|$ region. In order to calculate OBE process we employ the pseudovector coupling for πNN and ηNN interactions with the Gell-man–Sharp–Wagner (GSW) model for ϕ decays, i.e., the ϕ decays into $\gamma\pi$ ($\gamma\eta$) only through the intermediate ρ (ω) vector meson. Then the effective Lagrangian for the π -exchange reads

$$\mathcal{L} = \frac{g_{\pi NN}}{2M_N} \bar{N} \gamma^\mu \gamma_5 \boldsymbol{\tau} \cdot \partial_\mu \boldsymbol{\pi} N + g_{\phi\rho\pi} \epsilon^{\mu\nu\alpha\beta} \partial_\mu \phi_\nu \text{Tr}(\partial_\alpha \rho_\beta^0 \pi^0). \quad (5)$$

The effective Lagrangian for the η -exchange is obtained by the same manner. We use the πNN coupling constant $g_{\pi NN}^2/4\pi = 14.0$ [21] and rely on the SU(3) relation for the ηNN coupling constant, which gives $g_{\eta NN}/g_{\pi NN} = 0.26$ using $F/D = 0.565$. The effective coupling constants of $\phi\gamma\pi$ and $\phi\gamma\eta$ are related with $g_{\phi\rho\pi}$ and $g_{\phi\omega\eta}$ and determined from ϕ decay widths and the form factors are used for each vertex in the form of $(\Lambda^2 - M^2)/(\Lambda^2 - t)$, where M stands for the corresponding pseudoscalar meson mass [22]. Note that this OBE amplitude is purely real.

If the nucleon contains any $s\bar{s}$ sea quark admixture, the incoming photon can interact with the quark clusters, which gives the direct knockout mechanisms as shown in Fig. 1(c,d). They can be classified into $s\bar{s}$ -knockout and uud -knockout according to the struck quark cluster. To estimate the knockout contribution to the ϕ production, the proton wavefunction is approximated as

$$|p\rangle = A|[uud]^{1/2}\rangle + \sum_{j_{s\bar{s}}=0,1; j_c} b_{j_{s\bar{s}}} \left[[[uud]^{j_{uud}} \otimes [\mathbf{L}]^{j_c} \otimes [s\bar{s}]^{j_{s\bar{s}}}]^{1/2} \right], \quad (6)$$

where the superscripts $j_{uud} (= 1/2)$ and $j_{s\bar{s}} (= 0, 1)$ denote the spin of the corresponding cluster and (b_0, b_1) correspond to the amplitudes of the $s\bar{s}$ cluster with spin 0 and 1, respectively. The nucleon strangeness $|B|^2$ is then given by $|B|^2 = |b_0|^2 + |b_1|^2$ with the constraint $|A|^2 + |B|^2 = 1$. In order to have the positive parity ground state the orbital angular momentum between the clusters is constrained to be $\ell = 1$.⁷ We use the RHOQM for the hadron radial wavefunctions.

In the hadronic c.m. system, the amplitudes of the knockout process can be expressed as

$$T_{m_\phi, m_f; \lambda_\gamma, m_i}^{s\bar{s}} = iT_0^{s\bar{s}} \mathcal{S}_{m_\phi, m_f; \lambda_\gamma, m_i}^{s\bar{s}},$$

⁷ Detailed discussions on this form of the proton wavefunction can be found, e.g., in Refs. [5–8].

$$T_{m_\phi, m_f; \lambda_\gamma, m_i}^{uud} = i \left(T_0^{uud} \mathcal{S}_{m_\phi, m_f; \lambda_\gamma, m_i}^{uud} + T_1^{uud} \mathcal{Z}_{m_\phi, m_f; \lambda_\gamma, m_i}^{uud} \right), \quad (7)$$

where $T_0^{s\bar{s}}$ and $T_{0,1}^{uud}$ include the energy and momentum transfer dependence of the amplitudes. (For their explicit expressions, see Refs. [8,23].) Their spin structures are given as [6–8,23],

$$\begin{aligned} \mathcal{S}_{m_\phi, m_f; \lambda_\gamma, m_i}^{s\bar{s}} &= \sqrt{3} \sum_{\varrho} \langle \tfrac{1}{2} m_f \ 1 \ \varrho \mid \tfrac{1}{2}, m_i \rangle \xi_{\varrho}^{s\bar{s}} \lambda_\gamma \boldsymbol{\epsilon}_{m_\phi}(\phi) \cdot \boldsymbol{\epsilon}_{\lambda_\gamma}(\gamma), \\ \mathcal{S}_{m_\phi, m_f; \lambda_\gamma, m_i}^{uud} &= -\sqrt{3} \sum_{j_c, m_c, \varrho} \langle \tfrac{1}{2} m_f - \lambda_\gamma \ 1 \ \varrho \mid j_c m_c \rangle \langle j_c m_c \ 1 \ m_\phi \mid \tfrac{1}{2} m_i \rangle (1 - \delta_{\lambda_\gamma, 0}) \xi_{\varrho}^{uud}, \\ \mathcal{Z}_{m_\phi, m_f; \lambda_\gamma, m_i}^{uud} &= -\sqrt{\tfrac{3}{2}} \sum_{j_c, m_c, \varrho} \langle \tfrac{1}{2} m_f \ 1 \ \varrho \mid j_c m_c \rangle \langle j_c m_c \ 1 \ m_\phi \mid \tfrac{1}{2} m_i \rangle f_\mu \varepsilon_{\lambda_\gamma}^\mu(\gamma) \xi_{\varrho}^{uud}, \end{aligned} \quad (8)$$

with

$$\begin{aligned} f_0 &= \frac{5}{6} \left(1 + \frac{E_{p'}^L - \omega_\phi^L}{M_N} + 2 \frac{\mathbf{q}_L \cdot \mathbf{p}'_L}{E_{p'}^L M_N} \right), \\ \mathbf{f} &= \frac{5}{3M_N} \left[-\mathbf{q}_{\phi, L} + \frac{\mathbf{q}_L \cdot \mathbf{q}_{\phi, L}}{|\mathbf{q}_L|^2} \mathbf{q}_L + \frac{\nu_L}{E_{p'}^L} \left(\mathbf{p}'_L - \frac{\mathbf{q}_L \cdot \mathbf{p}'_L}{|\mathbf{q}_L|^2} \mathbf{q}_L \right) \right] + \frac{f_0 \nu_L}{|\mathbf{q}_L|^2} \mathbf{q}_L, \end{aligned} \quad (9)$$

and

$$\xi_{\pm 1}^{s\bar{s}} = \pm \frac{1}{\sqrt{2}} \sin \theta_{p'}, \quad \xi_0^{s\bar{s}} = \cos \theta_{p'}, \quad \xi_{\pm 1}^{uud} = \mp \frac{1}{\sqrt{2}} \sin \theta_{q_\phi}, \quad \xi_0^{uud} = \cos \theta_{q_\phi}, \quad (10)$$

where θ_α is the production angle of particle α in the $\gamma^* p$ laboratory frame.

Note that $T^{s\bar{s}} \propto b_0$ and $T^{uud} \propto b_1$ by the symmetry properties of the wavefunctions. Since all of these amplitudes are purely imaginary, they lead to strong interference with the diffractive process. In the kinematical region of our interest, $T_1^{uud} \mathcal{Z}^{uud}$ is suppressed by the $T_0^{uud} \mathcal{S}^{uud}$ term in the uud -knockout, and the $s\bar{s}$ -knockout dominates the uud -knockout at small $|t|$ region. However, the longitudinal photon can contribute only through the $T_1^{uud} \mathcal{Z}^{uud}$ part. Having the T -matrix, it is straightforward to construct the helicity amplitudes.

We give our predictions on the differential cross sections $d\sigma_{\gamma^*}/dt$ of virtual photoproduction in Fig. 2 at two energy regions: ($\sqrt{s} = 4.73$ GeV, $W = 2.94$ GeV, $Q^2 = 0.23$ GeV²), where some experimental data exist [19] and ($\sqrt{s} = 2.55$ GeV, $W = 2.15$ GeV, $Q^2 = 0.135$ GeV²), which is the energy region of a Jefferson Lab. proposal [24]. We see that the contributions from the associate mechanisms have similar dependence on the momentum transfer $|t|$ and the knockout process is suppressed by the diffractive process at small $|t|$. Thus it is very hard to distinguish them from the differential cross section measurements (in the forward scattering region).

However, as in the case of photoproduction, we find that some double polarization observables are very sensitive to the hidden nucleon strangeness. As typical examples, we consider beam-target

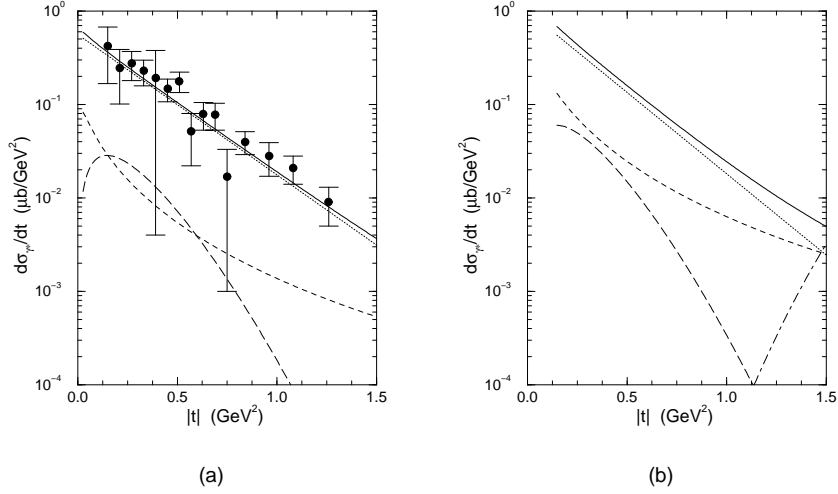


Fig. 2. The differential cross section for $\gamma^* + p \rightarrow \phi + p$ for (a) $\sqrt{s} = 4.73$ GeV, $W = 2.94$ GeV and $Q^2 = 0.23$ GeV² and (b) $\sqrt{s} = 2.55$ GeV, $W = 2.15$ GeV and $Q^2 = 0.135$ GeV². The dotted, dashed, long-dashed and dot-dashed lines are diffractive process, OBE, $s\bar{s}$ -knockout and uud -knockout processes, respectively, while the solid lines show the diffractive plus OBE predictions. In the knockout processes, $|b_0|^2 = |b_1|^2 = 0.5\%$ was assumed. The experimental data are from Ref. [19].

and beam-recoil double asymmetries, where the electron beams are longitudinally polarized. We define the beam-target asymmetry A_{BT}^z with the target nucleons polarized along their momentum direction and the beam-recoil asymmetry A_{BR}^x with the recoil nucleons polarized perpendicular to the momentum direction but in the scattering plane, which gives

$$A_{BT(BR)} = \frac{d\sigma(\uparrow\downarrow) - d\sigma(\uparrow\uparrow)}{d\sigma(\uparrow\downarrow) + d\sigma(\uparrow\uparrow)}, \quad (11)$$

where the arrows represent the helicities of the incoming electrons and target (or recoiled) protons. Note that these polarization observables are defined for $\Theta = 0$ where Θ is the angle between the normals to the electron scattering plane and the hadron production plane.

The results are given in Fig. 3, where the solid, dot-dashed and dashed lines are the results with $|B|^2 = 0, 0.5\%$ and 1.0% , respectively, where $|B|^2 \equiv |b_1|^2 + |b_2|^2$. In this paper, we focus on the forward scattering regions since the backward scattering regions may require not a little modifications on our models. In Fig. 3(a,b), we give the t -dependence of the observables A_{BT}^z and A_{BR}^x , while Fig. 3(c,d) show their Q^2 dependence at a given scattering angle in the γ^*p c.m. system. Our observations indicate that these double polarization observables in ϕ electroproduction are sensitive to the hidden nucleon strangeness and can be useful in investigating hidden nucleon structure. Even with less than 1.0% admixture of the nucleon strangeness, the deviations from the predictions without nucleon strangeness at forward scattering angles can be large enough to be detected by experiments. This is because the associated mechanisms have different spin structure. Figure 3(c,d) show that such deviation becomes larger for A_{BT}^z and is nearly flat for A_{BR}^x as Q^2 increases. Since the deviation decreases with increasing initial energies \sqrt{s} and W , the optimal energy region to observe this deviation would be near threshold.

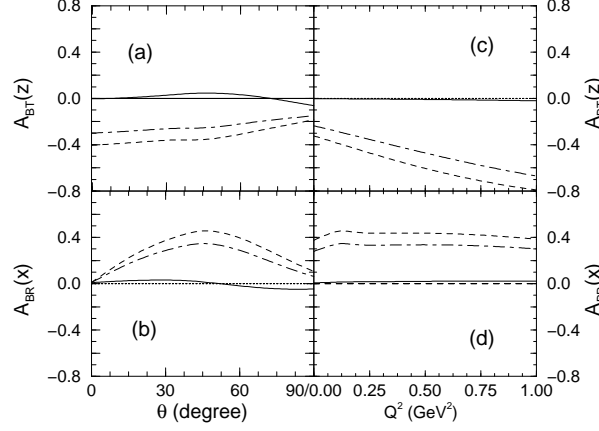


Fig. 3. Double polarization asymmetries with $\sqrt{s} = 2.55$ GeV and $W = 2.15$ GeV. (a) $A_{BT}^z(\theta)$ at $Q^2 = 0.135$ GeV², (b) $A_{BR}^x(\theta)$ at $Q^2 = 0.135$ GeV², (c) $A_{BT}^z(Q^2)$ at $\theta = 0^\circ$ and (d) $A_{BR}^x(Q^2)$ at $\theta = 45^\circ$, where θ is the scattering angle in the hadronic c.m. system. The solid, dot-dashed and dashed lines correspond to $|b_1|^2 (= |b_2|^2) = 0, 0.25\%$ and 0.5% , respectively. The phases of $b_{0,1}$ are chosen to be $+1$.

Since our results depend on the models for VDM and nucleon wave function, we have several comments on the possible modifications on our models. For example, there may be some corrections to the double polarization observables by the complex nature of the Pomeron exchange amplitude, which can interfere with the OBE part. The recent estimation of Ref. [22] shows that in the beam-target asymmetry of ϕ -photoproduction this interference is comparable to the effect of the knockout process with $|B|^2$ at the level of 0.1% at $\theta \rightarrow 0$ limit. So our results should be understood with this error range. Since the double asymmetries depends sensitively on the hidden nucleon strangeness at small energies, it would be also natural to see how much the final state interactions could change our results. Also the effect of direct ϕNN coupling, although expected to be small, and the role of intermediate hadron states might be considered for large scattering angle regions.

As a conclusion, we find that measurements of the double polarization observables in ϕ electroproduction may provide us with useful information on the nucleon structure, especially the hidden nucleon strangeness. It will be, therefore, very interesting if experiments of this kind can be carried out at current high-energy electron facilities.

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